Nationaal Lucht- en Ruimtevaartlaboratorium

National Aerospace Laboratory NLR

Executive summary

High Accuracy In-Flight Wing Deformation Measurements based on Optical Correlation Technique

Problem area

Deformations of wings are difficult to assess. By applying additional instrumentation to the wing, the wing properties would be changed. Therefore optical non-intrusive techniques are very suited to measure these deformations. In order to further develop these optical measurement techniques for project application in flight testing the EC 6th Frame work project AIM (Advanced In-flight Measurement techniques) was initiated. This paper that was presented at the 19th SFTE EC Symposium, Manching EADS, 22-24 September 2008, describes the measurement objectives, the preparations, flight trial activities and finally the obtained results.

Description of work

Adequate equipment was selected and partly procured. After laboratory tests components were installed into NLR's Fairchild Metro II research aircraft. Images of a speckled wing area were collected during various maneuvers, providing a wide range of wing loads. Images of the deflected wing were cross correlated with a reference situation using commercially available and in-house developed software.

Results and conclusions

Measured wing deflections were described according to a wing deflection model in terms of wing heave, torsion, twist and wing local behavior. Measurements proved to be feasible up to 0.2 mm accuracy.

Applicability

Apart from wing deformation measurements the technique is applicable for wing modes determination.

Report no.
NLR-TP-2008-718

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Report classification
UNCLASSIFIED

Date
November 2009

Knowledge area(s)
Flight Test & Instrumentation Systems

Descriptor(s)
optical measurement techniques
flight tests
wing deflection
Image pattern correlation technique

This report is based on a presentation held at the 19th SFTE (EC) Symposium, Manching (Germany), 22-24 September 2008.

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This publication has been refereed by the Advisory Committee AEROSPACE SYSTEMS & APPLICATIONS.

Customer	European Commission
Contract number	----
Owner	NLR
Division NLR	Aerospace Systems & Applications
Distribution	Unlimited
Classification of title	Unclassified
	November 2009

Approved by:

Author	Reviewer	Managing department
11/12/'09	11/12/'09	11/12/'09

Summary

NLR has developed a system for in-flight wing deformations measurement based on Image Pattern Correlation Technique (IPCT) as part of the AIM project ('Advance In-flight Measurement Techniques) funded by EC under FP6. The IPCT system was first tested in laboratory environment and subsequently integrated into NLR's Fairchild Metro II research aircraft. Aircraft integration tests were performed at the hangar, while also verification measurements of the aircraft-integrated IPCT system versus micrometer were made. The ground-based verification demonstrated the inherently high accuracy of the method. In flight the IPCT system was used successfully for wing deformation measurements. The aircraft wing deflection was measured under various load conditions ranging from 0g to 2.5g. Optical displacements of a randomly speckled part of the wing relative to a reference frame were determined using cross correlation techniques. These optical displacements were converted to geometrical wing deformations in a reference frame relative to the wing in reference condition.

Based on these geometrical wing deformation results a wing deflection model has been fitted. From this model various wing deflection parameters were determined and presented as function of the wing load. Parameters included e.g. change in wing heave, dihedral, torsion. Also the dynamic behavior of the wing, e.g. during landing, can be investigated with high accuracy using IPCT. The flight trial demonstrated the usefulness of the IPCT technique for high accuracy, static and dynamic in-flight wing deflection measurement.

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Abbreviations

AIM	Advanced In-Flight Measurement Techniques
BOS	Background Oriented Schlieren
CCD	Charge Coupled Device
IPCT	Image Pattern Correlation Technique
IRS	Inertial Reference System
NLR	National Aerospace Laboratory NLR
	(Nationaal Lucht- en Ruimtevaartlaboratorium *Dutch Abbreviation*)
PC	Personal Computer
PIV	Particle Image Velocimetry
SFTE (EC)	Society of Flight test Engineers (European Chapter)
UTC	Universal Time Coordinated

1 Introduction

Aircraft wings are subject to deflection. Designers must therefore take in-flight wing bending and torsion into account, so that structural loads are well taken care of and that the wing has optimum aerodynamic performance. Mathematical models are used to predict wing torsion and bending. To validate these models, measurement systems are required to measure actual wing deflection while the aircraft is in flight. Triangulation techniques are common practice for these measurements [Ref. 1] and in the past image processing techniques have been applied on a stripes pattern [Ref. 2].

The development of an innovative alternative wing deflection measurement system is part of the AIM (Advanced In-flight Measurement techniques) project in which various advanced non-intrusive measurement techniques are introduced for usage in flight testing by a consortium composed of partners from industry (Airbus, Eurocopter, Piaggio and Evektor), research organizations (DLR, ONERA, MPEI and NLR), a university (Cranfield University) and an airport service provider (Flughafen Braunschweig). These novel techniques are considered important for supporting future certification and in-flight research by taking advantage of these techniques efficiency, cost effectiveness, enhanced accuracy and capabilities. Several of those optical techniques such as PIV (Particle Image Velocimetry), PSP (Pressure Sensitive Paint), BOS (Background Oriented Schlieren), IRT (Infrared Thermography) and IPCT (Image Pattern Correlation Technique) have undergone considerable technological progress during the past decade and are already common practice in wind tunnel tests. These techniques shall be further developed such that they can be routinely applied to flight tests as well as to provide comprehensive planar information on various important parameters such as wing and propeller deformation, the planar pressure distribution on a wing, density gradients in strong vortices generated by airplanes and velocity flow fields generated near airplanes and helicopters. The main emphasis will be on development of methods requiring little or no modifications to existing aircraft. In this paper the development and application of an in-flight IPCT system for accurate fixed wing deflection determination is elaborated. The wing loading during flight produces an additional bending and twist, which may have a strong influence on circulation distribution and drag of the wing. With IPCT this bending and twist behavior can be investigated accurately under in-flight conditions.

2 Principles of IPCT

IPCT is an accurate planar, non-intrusive method for measuring deflections or deformations of objects under load conditions. The basic principle of IPCT is to compare two images of a pattern of tiny dots affixed to the surface (here of a wing) under inspection. First the image of the reference condition is taken. The second image is taken when the object is deformed. Employing two dimensional cross correlation algorithms, such as are used for the evaluation of PIV recordings (see Ref. [3]), the displacements of the tiny dots in a large number of interrogation areas on recorded images can be measured with sub-pixel accuracy, see figure 1.

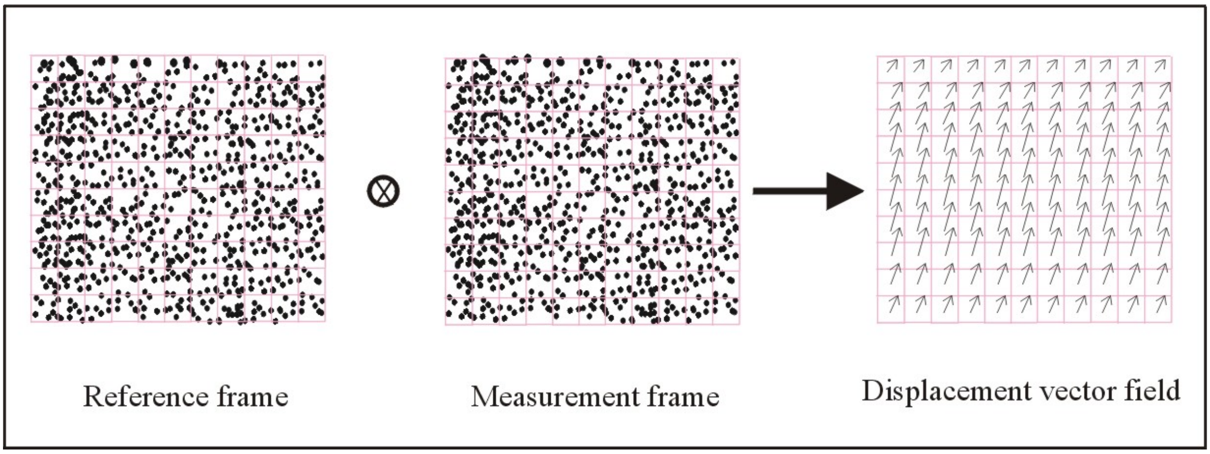

Figure 1 Principle of IPCT

The main advantage of IPCT is the simplicity of its basic experimental set-up: A foil furnished with a random dot pattern and a video camera combined with the high accuracy of the displacement field determination makes it a very interesting alternative for mature techniques used in flight testing such as photogrammetry and application of accelerometers.
In general a stereoscopic camera setup is needed for obtaining 3D geometrical displacements of a surface. In the case of wing deflection however, with its constrained deflection possibilities, only one camera will be sufficient when the geometry of the measurement setup is known.

3 Defined Objectives of In-flight IPCT

Within this project the IPCT technique was introduced into flight testing in progressive stages: from initial tests with ground-based instrumentation to in-flight feasibility study using a moderately sized research transport aircraft. With the feasibility demonstrated successfully a final validation test of the measurement technique is planned on a large commercial transport aircraft.

In a workshop the requirements for the IPCT wing deflection measurements during the feasibility study were defined from an industrial perspective. Using NLR's Fairchild Metro research aircraft the wing heave should be measured with accuracy better than 0.5 mm, while the wing torsion should be measured with 0.1° accuracy. Measurement of the wing's vibration modes must be feasible for frequencies up to 8 Hz. Measurement of aileron deformation, rotation and gap with the main wing's trailing edge should be feasible as well. Finally, from measurement-practical perspective the influence of a standard Plexiglas aircraft window instead of optical glass on the quality of the images and the influence of attaching the camera to the fuselage should be investigated.

4 Measurement Set-up and Instrumentation

Measurement setup and instrumentation selection was directly related with defined objectives and requirements. A wing chord in the order of 1 meter combined with 0.5 mm measurement accuracy leads to a camera resolution higher than 1k x 1k pixels. The requirement of measuring 8 Hz vibration modes leads theoretically to an image rate of higher than 16 Hz due to the Nyquist criterion: from a practical point of view a 25 Hz frame rate for the camera seems sufficient. An adequate, cost effective and easy to implement camera solution was found in a 30 frame per second, 1392x1040 monochrome digital camera with Gigabit Ethernet camera interface to a PC. Also important was the capability to trigger this camera externally in order to synchronize it in a stereoscopic setup or synchronize it with other measurement instrumentation, avionics or events. Using this external trigger both cameras could be excellently integrated with the Metro's real-time data acquisition system. For optimal results the dot pattern affixed on the wing must meet certain characteristics. The dot sizes as they are imaged on the cameras CCD array must be slightly exceeding the size of one pixel. In order to compensate the skewed angle of the camera view relative to the wing surface the dots must be stretched 1:5. In addition to dots also markers will be required at the foil to determine the course displacement and enable retrieval of matching interrogation areas for high accuracy IPCT displacement determination. In order to comply with these specific requirements a dot and "+" marker pattern generation software tool was developed. The generated dot and marker pattern was printed on self-adhesive polyethylene foil spanning the complete wing chord (1 meter spanwise at the tip) including the aileron at the wing tip area. The foil patterns were imaged by cameras at 5 to 6 meter distance. During the tests the attachment of the foil was good, while it could be removed easily from the wing and aileron afterwards.

Very important for good measurements was a stable and rigid fixation of the cameras relative to the wing. A rigid frame was designed for this fixation that was mounted at the four seat tracks at each side of the aisle on top of the wing root, inside the cabin.

Determination of the IPCT method's performance and capabilities was the aim of the project, therefore alternative measurements systems were included into the measurement setup, e.g. a three degrees of freedom accelerometer at the wing tip, an Inertial Reference System near the aircraft's centre of mass for determination of the load conditions and a synchro-meter installed at the aileron hinge for determination of the aileron rotation.

5 Wing Deflection Model

Final goal of wing deformation measurements was to describe the wing deformation in a geometrical coordinate system using a wing deformation model including all modes of static and dynamic wing deflection for which coefficients had to be determined. For describing the wing behavior the geometrical coordinate system had to be optimally aligned with the wing. It was decided to define the end of the wing's main spar at the wing tip at reference condition as the origin of this co-ordinate system. As x-axis direction the fuselage centre line direction was selected, while as y-axis the direction of the wing main spar was selected. In this way a plane is created naturally aligned with the wing where the line x=0 indicates the main spar inside the main wing surface. The z-axis was oriented normally to this plane, the upward direction positive.

In this local geometrical coordinate system the applied Wing Deflection Model for describing wing deflections as function of normal load under static conditions is the following:

$$z(n) = n^*(c_0 + c_x X + c_y Y + c_{xy} XY + c_{x2} X^2) + \varepsilon_z \qquad [1]$$

where:

- z: the local geometrical displacement perpendicular to the wing plane surface relative to reference (flight) condition (z=0 at wing surface, at n=1);
- n: normal load
- c_0: the heave: geometrical displacement perpendicular to plane surface at tip (x=y=z=0);
- c_x: the torsion: the X derivative of z;
- c_y: change in dihedral: Y derivative of z;
- c_{xy}: twist, X derivative of c_y
- c_{x2}: chord wise curvature, X derivative of c_x
- ε_z: residue relative to model (total of measurement errors and wing local behaviour)

6 Wing Coordinate Grid

Within the coordinate system described above the Metro's wing can in essence be described as a conical shaped body, the main wing profile being determined by carefully measuring its shape at the wing tip, where each span wise location is obtained by scaling in ratio with the distance to the cone's pole that is located in the extension of the wing tip. The wing surface is described by a grid, which lines in the y-direction are aligned with the cone and come together at the pole. The grid lines in wind direction are curved, equally spaced lines in the camera visual frame and straight, non-equally spaced lines in the geometrical frame (see figure 2).

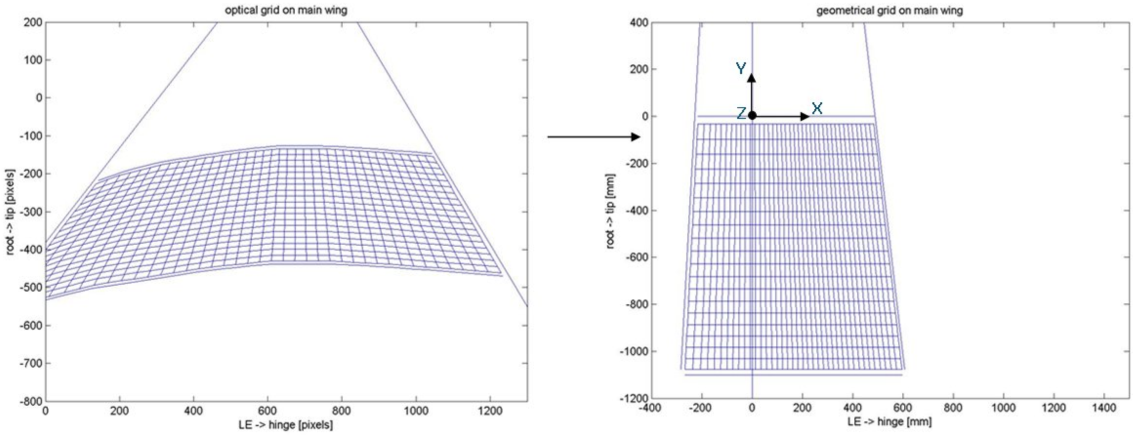

Figure 2 Impression of the wing in the camera visual frame and geometrical frame

By applying a diamond shaped interrogation area for cross correlation the contour of the cone's measurement area could be followed more accurately than with square interrogation areas.

7 Flight Test Data Processing Chain

Various software tools were required for processing the collected images together with measurement data from the reference systems and aircraft avionics:

- Marker tracking software for determination of the course wing displacements;
- IPCT cross correlation software;
- Software for camera image plane to 3D geometrical transformation;
- Software for determination of wing normal load;
- Software for (dynamic) wing deflection determination based on accelerometer;
- Software for determination of wing deflection model coefficients;
- Software for results visualisation.

All these functionalities were straightforwardly developed in Matlab. For IPCT cross correlation the commercially available PivView software package (version 2.4 from PivTec GmbH) was used in addition as alternative. PivView was less tailored for this specific application, but could be used for checking the Matlab code on correctness, while processing large datasets for dynamic verification worked more efficiently.

In general IPCT measurements need to be conducted using a two-camera stereoscopic measurement set-up in order to obtain a surface's 3D geometrical deformation results. For this wing geometry however, the transformation from pixel coordinates to 3D Cartesian coordinates can be done with one camera only taking advantage from constraints and geometry: wing movements in spar-wise direction are 0 while the measurement geometry is accurately known. The transformation between 2D pixel coordinates in the camera reference frame and the 3D wing aligned coordinate system can be obtained as a result as a combination of three 3D rotations together with a projection from 3D coordinates in the camera frame to 2D visual coordinates. A calibration of the camera's opening angle (mrad/px in both x and y direction) together with a conversion from visual displacements to local geometrical displacements completes the exercise.

8 IPCT versus Micrometer Verification

Prior to the in-flight IPCT test the IPCT's end-to-end measurement approach was verified in the hangar versus micrometer-based deflection measurements. Wing deflections were forced by filling the Metro aircraft's wing tanks with fuel. A first series of images were taken prior to the re-filling of the tanks serving as reference image. For an accurate measurement the aircraft was placed on struts. Wing deflections were measured by using a micrometer measuring the change in height of the wing tip relative to the hangar ground. In order to compensate for possible influence of fuel re-filling on the struts the height of the aircrafts fuselage near the strut was measured in addition. The filling of the tanks was to both left wing and right wing. Of the series of images one so-called measurement image was selected and correlated to the reference image. It should be noted that the obtained heave range was very limited in amplitude during this test, while also its deformation characteristics were expected to be different from the wing deformation in flight.

Heave results obtained by IPCT over the processed wing area were extrapolated to the micrometer measurement location at the wing. Using micrometers a 3.55 mm vertical deflection was measured at the reference point. Based on IPCT extrapolation 3.46 mm deflection (Matlab) and 3.47 mm deflection (PivView) were determined, which are within a 0.1 mm error bound in agreement with micrometer based measurements.

9 In-flight IPCT Measurements

After a shake down flight on August 17, 2007, which was made in order to verify correct functioning of all measurement systems involved, on August 24, 2007 a test flight for IPCT wing deflection was made in less busy airspace in the Northern part of the Netherlands. During this flight test all planned flight profiles were realized (see also figure 3).

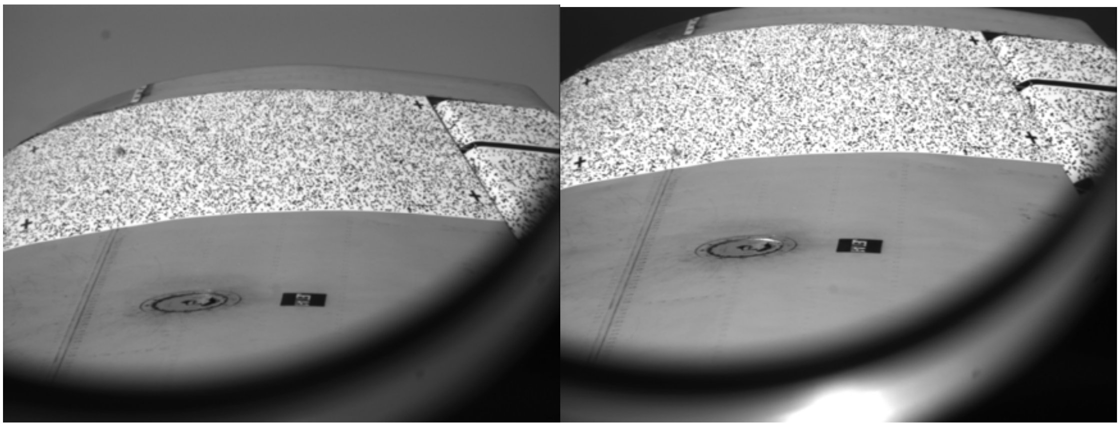

Figure 3 In-flight IPCT images: wing frames recorded at 0 g and 2 g

Together with taxiing, landing and some touch and go's various airborne maneuvers were executed: left and right turns up to 65° banking angle, parabolic flights, push-overs, steady side slips and aileron doublets, providing a wealth of recorded data, all with the intention of creating a large set of wing loads between 0 and 2.5 g. Every maneuver was combined with a period of straight level flight.

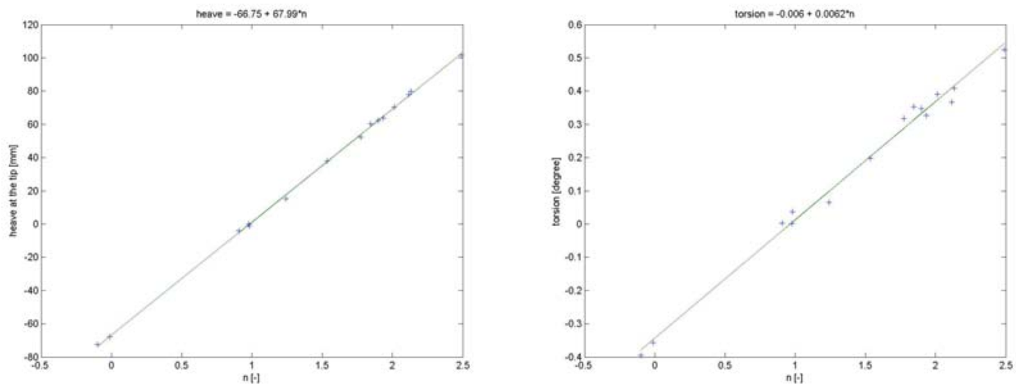

Figure 4 Vertical wing tip heave and wing torsion as function of the load factor

In the order of 140 mm difference in heave was measured between 0 g (parabolic flight) and 2 g (steep turning maneuver) maneuvers as can be seen in figure 4. The relative normal load values of the wing were accurately measured during each maneuver. It is based on the product of normal acceleration and the actual aircraft weight. Normal acceleration was measured by the

IRS, while the weight was determined by placing the completely instrumented and manned aircraft on an electronic balance prior to the flight. Measuring fuel consumption provided for the calculation of the accurate aircraft weight reduction during the complete flight.

10 IPCT Static Results

As the reference condition a straight level flight condition (load factor 1) was used, selected from the beginning of the flight. Vertical displacements at 0 g and 2 g over the measured wing plane relative to this reference are shown in figure 5. The displacements grow smoothly towards the wing tip. Also the torsion is clearly visible: the highest deflection values are obtained at the wing tip leading edge.

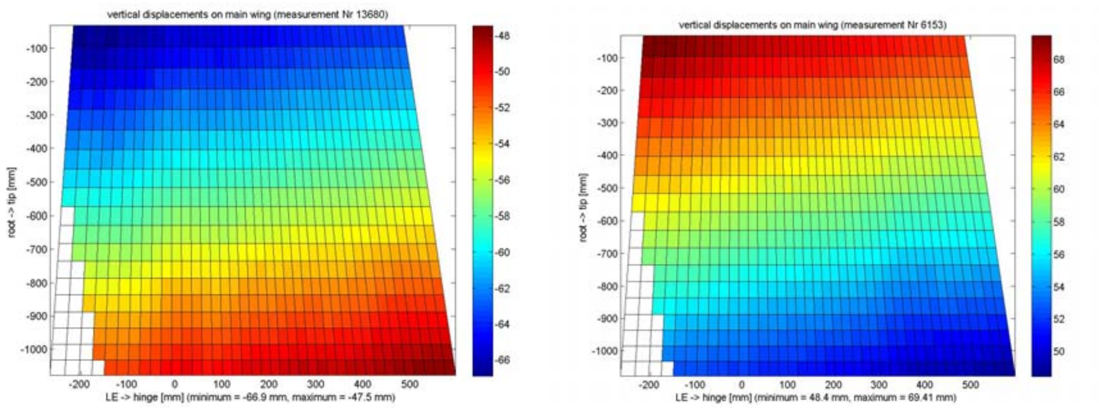

Figure 5 Vertical displacements of wing surface at 0 g and 2 g

At 2 g 0.39° torsion was measured, while the 0 g parabolic maneuver showed -0.36° torsion relative to the reference. From these measurements under various load conditions all coefficients of the Metro's wing deflection model [1] could be obtained by least square fit: figure 4 shows the heave at the tip and the torsion at the wing tip both as a function of load. This latter graph shows the torsion measurement accuracy to be better than 0.05° (2σ).

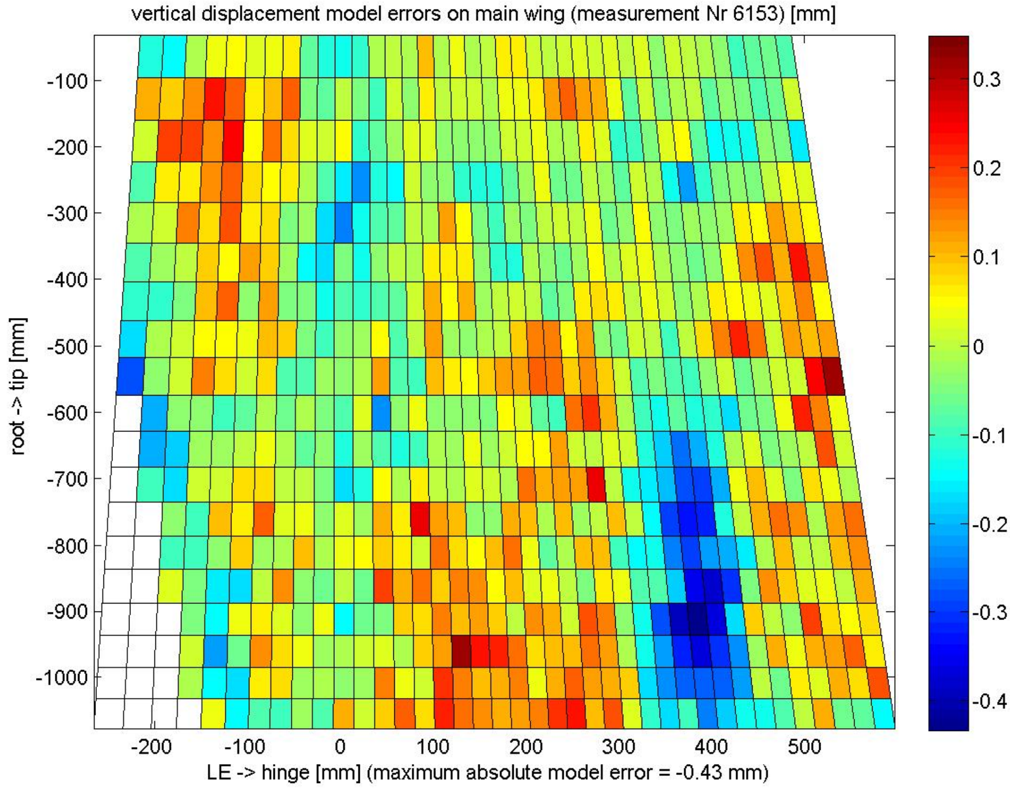

Figure 6 Vertical displacement model errors on main wing at 2 g

Fitting the coefficients of the obtained wing deflection model for each wing grid point and subtracting these from the measured local grid point deflection values leaves the measurements residues. From figure 6 showing vertical displacement model residues on the main wing measured at 2g, it is clear that the model fit is, in this case, better than 0.5 mm on all locations. It also shows a ‘buckling area’ at the right lower part that should be characterized as real local deflection behavior of the wing surface. Architecture schemes of the wing construction show a reduced local wing support. Locally the ribs and spars supporting the plating are less dense. Model residues are thus composed of two contributions, local wing behavior and measurement errors. Isolation of the wing’s local behavior revealed a measurement error in the order of 0.2 mm.

Figure 7 shows the correlation of the wing’s local behavior with normal load. It shows the negative correlation with normal load of the wing area directly supported by the main spar, clearly indicating the spar’s reluctance to follow the wing’s heave due to aerodynamic forces.

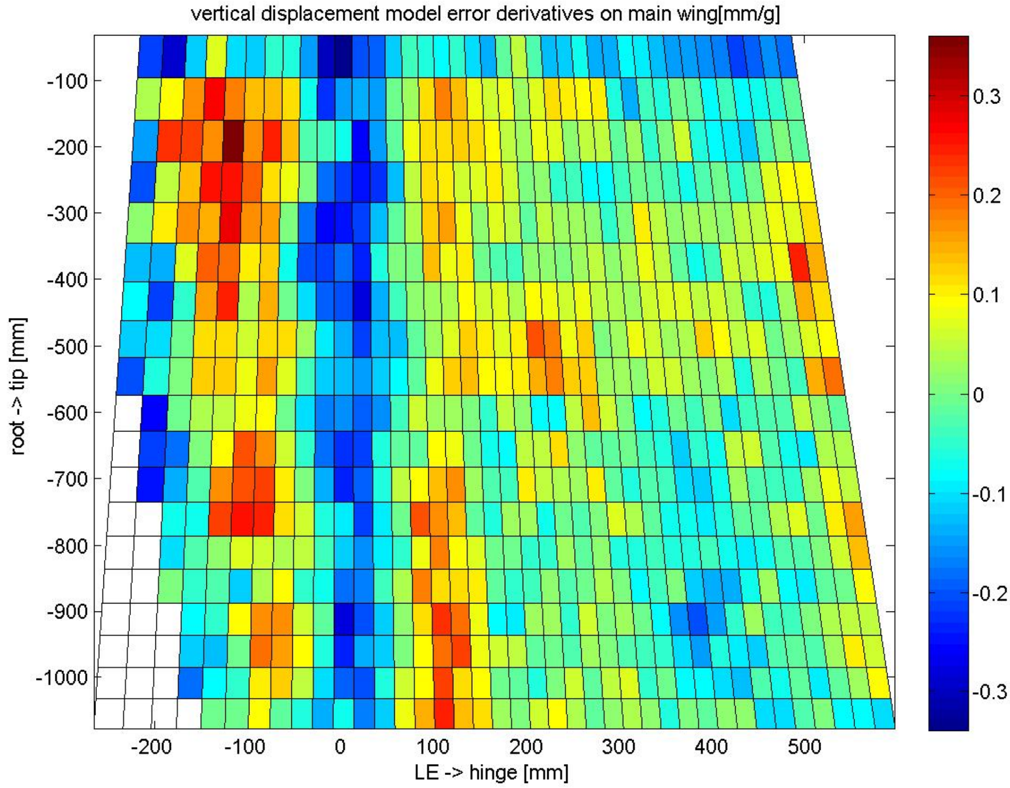

Figure 7 Vertical displacement model error derivatives with respect to loads δ Δz/ δn in [mm/g]

11 IPCT Dynamic Results

During the flight no conditions of free wing vibrations could be observed, due to continuous inputs of stimuli. During the ground tests at the hangar these free wing vibrations could be observed after bringing the wing into vibration by hand. Although being only at very small amplitude of ~0.7 mm and lasting for about 2 seconds, the wing's free vibration could be convincingly measured by IPCT. Figure 8 shows the wing's free vibration measured both by accelerometer at the wing tip and by IPCT, which are in excellent agreement. A power spectrum derived from the dynamic IPCT measurements shows two eigen frequencies of approximately 4.5 and 8 Hz. A model fit through the measured IPCT points provides optimal fit for two eigen frequencies of 4.54 Hz (damping 1.11 s) and 7.88 Hz (damping 0.94 s).

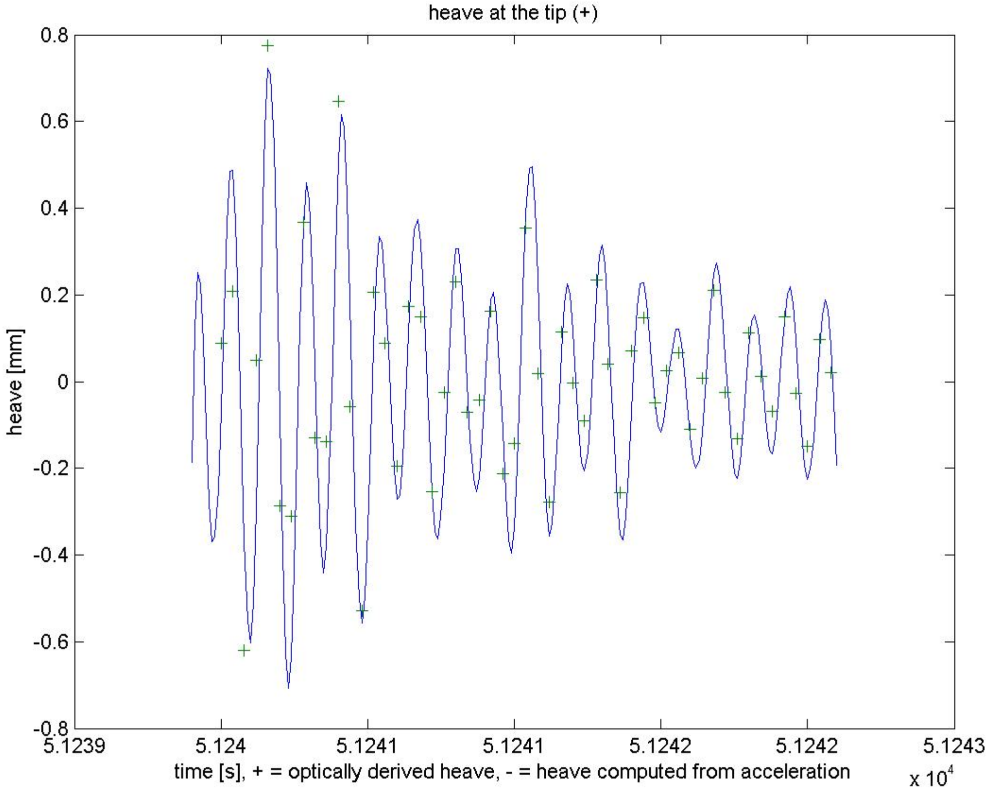

Figure 8 Wing tip free vibrations, measured by accelerometer and IPCT

12 Aileron Measurement Results

In addition to the main wing, also the in-flight aileron deflection has been characterized using IPCT: the aileron heave, aileron rotation around the hinge and changes of the aileron gap with the main wing's trailing edge have been determined.

In comparison to the main wing the aileron has as complicating characteristic its rotating capability making the cross correlation of reference image and measurement image more problematic. In order to enable IPCT-based deflection measurement of the rotated aileron a database of 250 reference images was made containing a complete aileron rotation sweep. From this database of aileron reference images, the one is selected that provides maximal correlation with the measurement image. A stripe on the aileron is used to retrieve a course indication of the rotation of the aileron. IPCT-based aileron deflection figures are determined relative to this reference image. In this way the deflection of wing and aileron was determined relative to a ground reference. For a straight level flight condition the aileron heave and torsion could very well be determined, in line with the main wing. As a result the following aileron deflection model could accurately be estimated in line with that of the main wing:

$$z = c_0 + c_x X_a + c_y Y + c_{xy} X_a Y + \varepsilon_z \qquad [2]$$

where all coefficients are defined similar to [1] except:

X_a coordinate in wind direction parallel to fuselage centre line: $X_a(Y) = X - X_{hinge}(Y)$

Note that the coefficient c_x describes the aileron's rotation.

The vertical geometrical displacements between main wing trailing edge and aileron front just behind the main wing trailing edge, the 'gap' (see figure 9), has been determined by subtraction of the displacement of the wing trailing edge and aileron below the main wing trailing edge. As was expected the gap size strongly varies in span wise direction. The gap deformation tends to be zero at the aileron hinges, which here were located at 450 mm and 1220 mm from the tip.

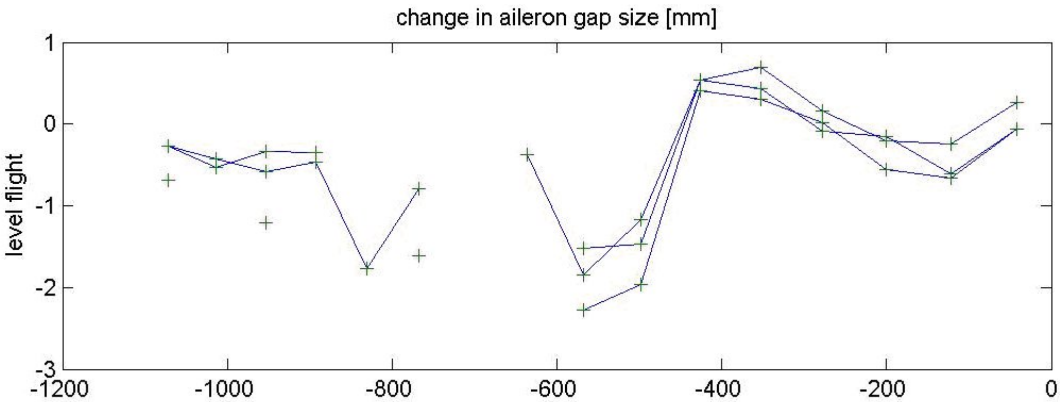

Figure 9 Change in aileron vertical gap size of level flight vs. ground reference

13 Simultaneous Measurement of both Cameras

During taxiing chaotic, highly dynamic vibrations of the wing were observed, caused by repeated receipt of stimuli from the taxiway surface. It was considered very interesting to collect a simultaneous image sequence of these motions using both installed cameras and compare the obtained local displacement results. The sequence of results from both cameras will be in line with each other then and only then if the following conditions are adequately met:

- The camera image triggers are correctly synchronized;
- The camera mounting frame is rigid enough while cameras and frame are adequately fixed to the aircraft seat track, not allowing uncorrelated camera motion relative to the reference frame;

- The camera-visual to geometrical transformations are correctly and accurately calculated;
- As one of the cameras was mounted behind standard Plexiglas aircraft window, the Plexiglas window shall not disturb or deteriorate the image too much.

Figure 10 shows the comparison of the wing deflection measured at one wing coordinate obtained by both cameras. It shows that measurements from both cameras are in line with each other, well within a mean error bound of 0.5 mm (1 σ). This result convincingly shows the correctness and robustness of the IPCT measurement technique, while it also shows that IPCT can very well be performed from behind a (cleaned) Plexiglas standard aircraft window.

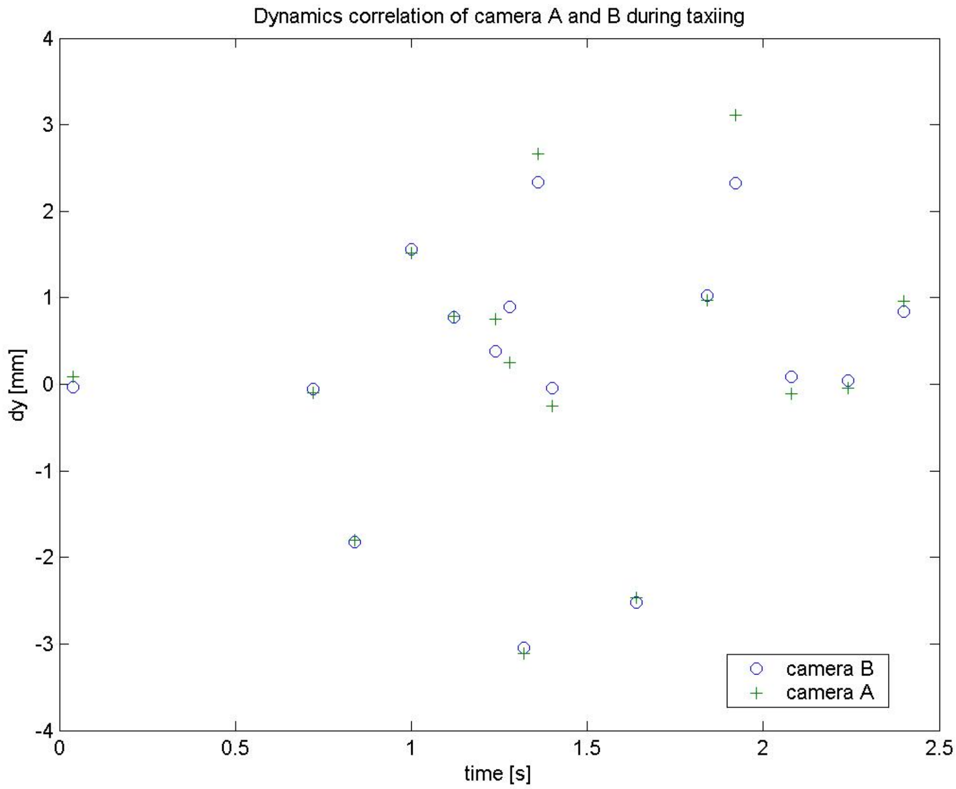

Figure 10 Correlation of dynamic deflection results from camera A and B during taxiing

14 Reference Frame Issues

When performing high accuracy deformation measurements in a flexible environment such as an aircraft, finding an adequate reference frame for the measurement is an important issue. One should always keep in mind that displacements are measured relative to the camera's viewing direction. During our in-flight IPCT measurements also small, finger sized camera heads were mounted on top of the fuselage. When comparing the deflection results obtained by these cameras with the results from the cabin mounted cameras, considerable differences were noticed, which we attribute to elastic deformations of the fuselage under various load conditions. In our measurement set-up the seat rails on both sides of the aisle were adopted as the reference frame for the cameras. However, even between these two cabin-mounted cameras small rotation differences were measured unexpectedly due to deformation of the seat rails. Possibly the most practical approach would be to discuss with the end-user of the measurement data the selection of the optimal reference frame, based on the kind of measurements that will be made. The quantitative values of these camera position and attitude transformations should be assessed, e.g. by mounting additional cameras on the camera frame viewing and measuring displacements relative to the opposite part of the cabin. This procedure was proposed and adopted in later Airbus A380 wing deformation measurements.

Conclusions

The in-flight IPCT measurements show that this technique is suitable for high accuracy wing deflection measurements. All objectives that were defined by aircraft manufacturers were met:

- The wing heave measurement accuracy objective of 0.5 mm (for the Metro aircraft) was met; A measurement accuracy in the order of 0.2 mm was obtained.
- The wing torsion measurement accuracy objective of 0.1° was met: obtained accuracy was better than 0.05°;
- It is feasible to accurately measure the relationship between the wing heave and the normal load;
- Wing dynamic deformations have been measured during landing and taxiing, while wing vibration eigen values have been measured on the ground;
- The aileron deflection and main wing – aileron gap change can be measured;
- No degradation has been observed in the quality of the results through a standard Plexiglas aircraft window versus results obtained through optical flat glass

The installation and application of instrumentation and speckles on the aircraft for wing deformation measurements with IPCT required only a limited effort. The instrumentation developed is suitable for flight test operations. From these facts, combined with the measurement performance and capabilities, which are considered better than legacy techniques such as photogrammetry and accelerometer, it is concluded that the IPCT measurement method and its implementation in the applied set-up are well suited for future in-flight wing deformation measurements.

Acknowledgements

The work described in the paper is executed as part of the AIM project which is supported by the European Commission.

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